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(6) Effect of Rate and Level of Lowered Finger Surface Temperature on Manual Performance

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Thirty-two subjects were tested on six manual tasks when the right forefinger surface temperature was either not lowered, for the control condition, or lowered to temperatures of 65°, 55°, and 48° ~~Fahrenheit (18.3°, 12.8°, and 8.9° Centigrade)~~ after 5 or 50 minutes of cooling. Performance on all tasks decreased with lowered surface temperature. The level of finger surface temperature associated with impaired performance and the extent of the performance decrements associated with additional cooling varied across tasks and cooling rate. The differential effects of local cooling on manual performance across tasks and cooling rates were analyzed in terms of the differential susceptibility of hand function to parameters of cold exposure and the selective requirements across aspects of manual performance for unimpaired functioning of the hands and arms.

The purpose of the present study was to investigate the effects of rate of cooling and level of lowered hand skin temperature on manual performance. Performance was measured on a battery of six different tasks under normal ambient temperatures and when finger surface temperature was lowered to 65°, 55°, or 45° Fahrenheit (18.3°, 12.8°, or 7.2° Centigrade) after 5 or 50 minutes of exposure to varying levels of ambient temperature and air movement.

Exposure of the hand to cold results in a lowering of hand skin temperature and in decrements in performance on manual dexterity tasks (Bartlett & Gronow, 1952; McCleary, 1953). Cold-impaired manual performance is assumed to result from a loss of cutaneous sensitivity (Mackworth, 1953), changes in the characteristics of synovial fluid in the joints, (Hunter, Kerr, & Whillans, 1952), or a loss of muscle strength (Hellstrøm, 1965). The relative contributions of these and other unspecified factors to cold-induced manual performance decrements are assumed to be dependent upon the parameters of cold exposure and the type of manual performance involved. Parameters of cold exposure include level of hand skin temperature, rate of cooling, and locus of cooling.

The determining surface temperature for impaired manual performance varies from 86° Fahrenheit (30° Centigrade) to below 55° Fahrenheit (12.8° Centigrade) depending upon the task being performed and the part of the body being cooled. Thus, lowering forearm muscle temperature below about 86° Fahrenheit (30° Centigrade) results in gradual reduction of hand grip strength (Hellstrøm, 1965); lowering finger surface temperature below 68° Fahrenheit (20° Centigrade) impairs the rotation of an object between the thumb and forefinger (Hellstrøm, 1965); and lowering finger surface temperature from 60° to 55° Fahrenheit (15.6° to 12.8° Centigrade) impairs knot-tying performance (Clark, 1961).

In an investigation of the effect of rate of cooling on knot-tying performance, Clark and Cohen (1960) found that slow cooling to a 45° Fahrenheit finger temperature resulted in greater knot-tying decrements than did fast cooling to the same temperature. The difference between the slow and the fast cooling conditions persisted when the hands were rewarmed by exposure to normal ambient tem-

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peratures, but did not persist when an electric muff was used to rewarm the hands. Clark and Cohen (1960) inferred that slow cooling rates resulted in relatively lower subsurface temperatures and attributed the rewarming difference to the relative effectiveness of radiant heat in raising subsurface temperatures.

The effect of radiant heat on hand subsurface temperature was inferred also by Lockhart and Kiess (1971) when they found that the application of radiant heat to bare hands during cold exposure prevented or alleviated cold-impaired manual performance, but had only a slight effect on hand surface temperatures. In that study the relative effectiveness of radiant heat applications in preventing cold-impaired manual performance varied across tasks. It is hypothesized that those tasks for which radiant heat was relatively more successful in preventing cold impairment (Purdue Pegboard assembly and knot-tying) would be more susceptible to slow cooling effects (an inferred greater reduction in subsurface temperatures) than those tasks (block packing, block stringing, and screw tightening) which were relatively less affected by radiant heat applications during cold exposure. The present study was conducted to test this specific hypothesis as well as to determine the limiting finger surface temperature for unimpaired performance across a battery of manual performance tasks.

Method

Subjects

The subjects were 32 enlisted men who volunteered for assignment to the Climatic Research Laboratory of the United States Army Natick Laboratories. The subjects ranged in age from 19 to 25 years and had previous experience in cold exposure experiments.

Apparatus and Tasks

The experimental sessions were conducted in an environmental chamber with an ambient temperature of approximately 75° Fahrenheit (23.9° Centigrade). To attain various levels of finger surface temperature with two cooling rates (5 versus 50 minutes of exposure to varying levels of ambient temperature and air movement), the subjects placed their hands inside a large hand-cooling box with a thermostatically controlled cooling element. The subject placed his hands in the box through two armholes and viewed the interior of the box through a window. Two small variable speed fans were mounted inside the cooling box in order to supply varying levels of wind movement. Two mock hand-cooling boxes consisting of large pieces of plywood with armholes and a window were used during the practice session. Hand skin temperature was measured by copper constantan thermocouples and recorded by a Leeds-Northrup Speedomax recorder.

The following tasks were used: block packing, block stringing, Craik screw, knot tying, Purdue Pegboard assembly, and screw tightening. The block-packing task consisted of packing 2.54-centimeter blocks, one at a time, into a box. For the block-stringing task, each subject strung 2.54-centimeter blocks, with a hole through each face, onto a needle and thread. The Craik screw task consisted of metal screwheads, five millimeters in diameter located seven millimeters apart along the face of a metal bar. The subject, using his thumb and forefinger, relocated each screw one at a time. For the knot-tying task, the subject was required to tie a standard knot on each of a number of strings hanging from a rotatable disk. On the Purdue Pegboard assembly task, the subjects constructed peg, washer, collar, washer units. Screw-tightening consisted of tightening and loosening vertically mounted, spring-loaded screws with a screwdriver.

Procedure

Prior to testing, each subject practiced on each task for five days. For four tasks, there were five practice trials per day with a trial defined as 30 blocks packed, 15 blocks strung, six small screws relocated, or three screws turned five complete turns in and five turns out. For the remaining two tasks, there were 10 practice trials per day. Twenty knots were tied, or six peg, washer, collar, washer units were assembled per trial. During practice, which was conducted at an ambient temperature of 70° Fahrenheit (21.1° Centigrade) the subjects worked in pairs (one from each rate of cooling group) at the mock hand-cooling boxes. The subjects practiced with thermocouples taped on two fingers, back of hand, and forearm of both the right and the left arms, but the thermocouple output was not recorded. The subjects wore the standard Army fatigue uniform during the practice days.

For the experimental sessions, the 32 subjects were divided randomly into four groups of eight subjects each. These groups were tested during consecutive weeks with each group receiving, in a different order, the four finger surface temperature conditions: a control condition with no cooling and three conditions in which finger surface temperature was lowered to either 65°, 55°, or 45° Fahrenheit (18.3°, 12.8°, 7.2° Centigrade). Over the four groups, the order of presentation of the temperature conditions was counterbalanced across days. Within each group, four subjects were tested in the morning and four in the afternoon. In both the morning and the afternoon, the desired finger surface temperature condition was attained after either 5 minutes of cold exposure (half of the subjects) or 50 minutes of cold exposure (the other half of the subjects).

On any given test day, a subject entered the temperature-controlled chamber (75° Fahrenheit, 23.9° Centigrade) dressed in the standard Army fatigue uniform. Each subject removed the fatigue shirt, and thermocouples, secured by adhesive tape, were placed on (*a*) both forefingers and both little fingers at the base of the nail; (*b*) the dorsal surface of both hands; and (*c*) both forearms. Each subject sat on an adjustable stool with both hands in the hand-cooling box. Box temperature and air movement were manipulated in order to achieve a given surface temperature condition within the required exposure period. Box temperature varied from 0° Fahrenheit (−17.8° Centigrade) up to approximately 84° Fahrenheit (28.9° Centigrade). The variable speed fans were off (0 miles per hour) or on with air movement varing from 1.5 to 16.1 miles per hour. After the 5- or 50-minute exposure period, the subject performed three consecutive 30-second trials on each of the six tasks. Order of task presentation was partially counterbalanced across conditions and within a rate of cooling group. The task score during cold exposure was the mean across three 30-second trials of the number of task components completed in 30 seconds.

While each subject was performing the tasks, box temperature and wind movement continued to be manipulated in order to maintain the required surface temperature. The surface temperature of the right forefinger was used as the criterion.

Experimental design. The data for each task was analyzed separately using a Latin square analysis of variance design in which sequence, rate of cooling, and time of day were between-subjects variables and order (days), right-forefinger surface temperature, and square uniqueness were the remaining variables. The four orders of presentation of the finger surface temperature conditions represented four different sequences. Rate of cooling referred to the 5-minute (fast cooling) and 50-minute (slow cooling) exposure periods to attain criterion surface temperatures. Test sessions were conducted either in the morning or in the afternoon (time of day). The test sessions were conducted across four consecutive days or orders. The right-forefinger surface temperature of each subject was either not cooled (control) or lowered to approximately 65°, 55°, or 45° Fahrenheit (18.3°, 12.8°, or 7.2° Centigrade). These temperature conditions were presented in accordance with the Latin letters in the design. Significant main effects and interactions were analyzed further using the Newman-Keuls test.

TABLE 1

MEAN AND STANDARD DEVIATION OF SURFACE TEMPERATURES (° FAHRENHEIT) AT DIFFERENT RECORDING SITES FOR EACH SURFACE TEMPERATURE CONDITION

Recording site	Cooling rate	[illegible]nd condition ([illegible]nrenheit)				Left-hand condition (° Fahrenheit)			
		Control	65°	55°	45°	Control	65°	55°	45°
Forefinger	Fast								
	$\bar{X}$	94.1	66.1	56.7	47.[illegible]	93.6	65.2	56.1	47.6
	SD	2.0	3.3	1.8	2.9	2.2	2.0	2.0	1.8
	Slow								
	$\bar{X}$	93.4	64.4	56.8	49.0	93.8	64.4	56.6	47.0
	SD	2.2	3.4	2.7	3[illegible]	2.4	3.0	2.4	1.8
Little finger	Fast								
	$\bar{X}$	92.9	66.[illegible]	57.6	49.4	93.6	68.6	59.4	51.0
	SD	1.9	5.1	4.1	3.8	2.0	7.5	5.0	2.7
	Slow								
	$\bar{X}$	92.2	61.4	56.0	46.8	93.9	63.4	56.2	49.2
	SD	2.5	3.7	3.9	[illegible]	2.4	3.5	3.4	3.4
Back of hand	Fast								
	$\bar{X}$	93.8	73.0	66.3	55.6	92.2	75.4	66.4	57.3
	SD	1.8	3.8	5.4	4.8	3.1	5.5	6.8	4.1
	Slow								
	$\bar{X}$	92.8	75.2	68.0	52.6	93.1	76.7	65.4	54.4
	SD	2.7	3.3	5.3	5.4	4.6	2.5	4.9	4.7
Forearm	Fast								
	$\bar{X}$	92.9	81.2	79.8	7[illegible]	9[illegible].6	83.2	79.9	76.8
	SD	1.8	4.2	6.2	[illegible]	4.2	4.0	4.4	3.7
	Slow								
	$\bar{X}$	93.2	83.0	81.2	7[illegible]	92.4	83.4	82.0	75.2
	SD	3.2	3.4	2.8	[illegible]	4.2	3.6	3.8	8.1

RESULTS

Surface Temperature

The mean surface temperatures at both forefingers, little fingers, backs of hand, and forearms while the tasks were being performed are presented in Table 1. The attempt to maintain a 45° Fahrenheit (7.2° Centigrade) right-forefinger surface temperature was not successful. At all temperature conditions, surface temperatures at the little fingers were similar to those at the forefingers and, for the 55° and 45° Fahrenheit conditions, the temperatures of these fingers were below those levels generally associated with impaired manual performance.

TABLE 2

MEAN TASK SCORE FOR EACH SURFACE TEMPERATURE CONDITION

Task	Condition (° Fahrenheit)			
	Control	65°	55°	45°
Block packing	30.1	29.8	28.8	26.9
Block stringing	14.5	14.1	13.4	11.3
Craik screw	13.5	12.9	11.7	10.0
Knot tying	17.2	16.4	15.1	12.3
Purdue Pegboard	23.7	22.2	20.1	14.6
Screw tightening	33.6	31.1	27.5	21.6

Note. The differences between scores within each task that are not underlined are significant ($p < .05$) using the Newman-Keuls test.

Task Performance

The main effect of temperature was significant in the analysis of the data for all tasks: block packing ($F = 17.15$, $df = 3/48$, $p < .001$); block stringing ($F = 48.80$, $df = 3/48$, $p < .001$); Craik screw ($F = 28.23$, $df = 3/48$, $p < .001$); knot tying ($F = 44.29$, $df = 3/48$, $p < .001$); Purdue Pegboard assembly ($F = 92.21$, $df = 3/48$, $p < .001$); screw tightening ($F = 56.45$, $df = 3/48$, $p < .001$). Rate of cooling was a significant main effect only in the analysis of the block-stringing data ($F = 4.55$, $df = 1/16$, $p < .05$). The Rate of Cooling × Temperature interaction was significant in the analysis of the block stringing ($F = 5.86$, $df = 3/48$, $p < .005$), Craik screw ($F = 3.73$, $df = 3/48$, $p < .025$), and Purdue Pegboard assembly ($F = 5.35$, $df = 3/48$, $p < .005$) data. For the block packing data, the Rate of Cooling × Temperature interaction F ratio was equal to 2.34 with $p < .10$. The results of the Newman-Keuls analysis of the means from the significant surface temperature effects are presented in Table 2. Figures 1 and 2 present mean task scores as a function of finger surface temperature conditions for fast and slow rates of cooling. The results of the Newman-Keuls analysis of the significant ($p < .05$) Rate of Cooling × Temperature interactions are presented in the figures as solid lines encompassing those points which are not significantly different from one another.

The main effect of surface temperature on performance differed across tasks (see Table 2). When averaged across cooling rate, mean block-packing, block-stringing, Craik screw, and knot-tying scores were not significantly lower than those for the control condition until finger surface temperature was lowered to 55° Fahrenheit. With additional cooling, performance on these four tasks was significantly lower than performance at 55° Fahrenheit. For the block-packing task alone, performance at 55° Fahrenheit did not differ significantly from that at 65° Fahrenheit. Purdue Pegboard assembly and screw-tightening performance was impaired, relative to the control condition, at the 65° Fahrenheit finger surface temperature and became progressively worse as surface temperature decreased.

The means from the significant Rate of Cooling × Temperature interactions were analyzed further using the Newman-Keuls test. Mean scores significantly lower than those for the control condition occurred at 55° Fahrenheit with slow cooling and at 45° Fahrenheit with fast cooling for the block-stringing task and at both 55° Fahrenheit surface temperature conditions for the Craik screw task. Performance on both tasks continued to decline only for the 45° Fahrenheit, slow rate condition (Figure 1). Differential rate effects on performance as a function of temperature were supported by subsequent analyses of variance in which the control data were excluded. The Rate of Cooling × Temperature interaction was significant in the analysis of the block-stringing ($F = 3.78$, $df =$

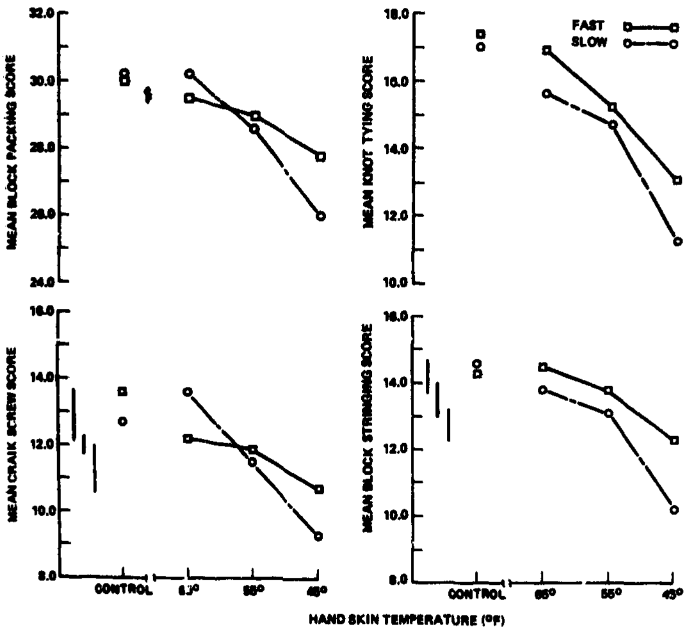

FIGURE 1. Mean block-packing, block-stringing, Craik screw, and knot-tying scores as a function of finger surface temperature for fast and slow rates of cooling.

2/60, $p < .05$) and the Craik screw ($F = 5.32$, $df = 2/60$, $p < .01$) data.

Purdue Pegboard assembly performance was impaired relative to the control condition at 65° Fahrenheit with slow cooling and at 55° Fahrenheit with fast cooling. Mean scores for these two conditions were not different from each other. The 55° Fahrenheit, slow cooling, the 45° Fahrenheit, fast cooling, and the 45° Fahrenheit, slow cooling conditions resulted in a continued worsening of Purdue Pegboard assembly performance (Figure 2). The absence of differential rate effects for the lower temperature conditions was supported by subsequent analysis in which the control data was excluded. In that analysis, the main effects of rate of cooling ($F = 4.56$, $df = 1/30$, $p < .05$) and finger surface temperature ($F = 81.26$, $df = 2/60$, $p < .001$) were significant. The interaction term ($F = 2.76$, $df = 2/60$, $p < .10$) was not significant.

DISCUSSION

In the present experiment, rate of cooling did not affect knot-tying performance. Previously, the effects of rate of cooling and level of hand skin temperature on knot-tying performance had been found to interact (Clark & Cohen, 1960). In spite of the many differences in procedure between the two studies, it is proposed that the failure in the present study to attain the 45° Fahrenheit criterion temperature (mean right-forefinger surface temperatures were 47.9° and 49.0° Fahrenheit (8.8° and 9.4° Centigrade)) underlies the absence of a significant temperature level by cooling rate interaction for knot-tying performance.

The results of the present experiment have both practical and theoretical implications. In considering the practical implications, developers of equipment to be operated by man in cold climates and designers of protective equipment have been concerned with the level of cooling associated with impaired performance, the extent of impairment, and the aspects of manual performance impaired by cold exposure. Such information in the form of the approximate mean percentage of reduction in performance as a function of level of hand skin temperature and cooling rate is presented in Table 3 for each task used in the present study. As can be seen in the present context, the limiting hand skin temperature for unimpaired manual performance during cold exposure depended upon the task and the rate of cooling. For a given task, initial cold impairment may occur when finger surface temperature is lowered slowly to 55° Fahrenheit (12.8° Centigrade). If the fingers have been cooled rapidly, initial cold impairment may not appear until the surface temperature has reached 48° Fahrenheit (8.9° Centigrade). For still another task, initial cold impairment may be present with surface temperatures as high as 65° Fahrenheit (18.3° Centigrade) with slow cooling or 55° Fahrenheit (12.8° Centigrade) with fast cooling. One of the engineering options to alleviate cold-impaired performance suggested by these results is the design of equipment to modify the tasks required. Modifications which result in larger objects to be manipulated and which require less joint movement presumably should re-

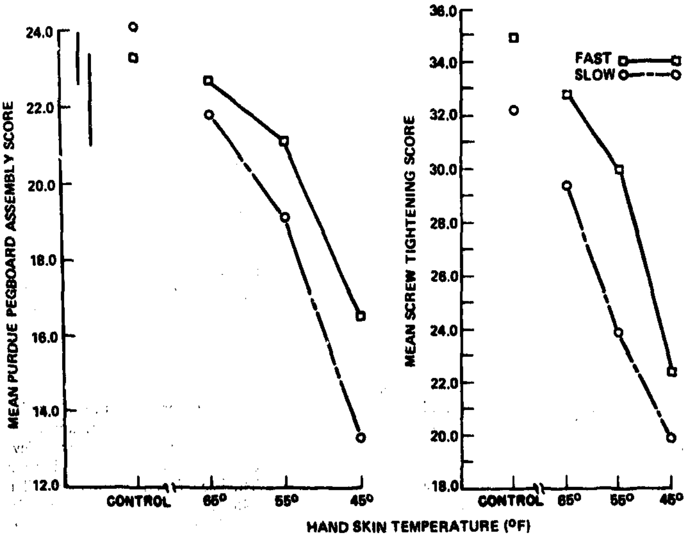

Figure 2. Mean Purdue Pegboard assembly and screw-tightening scores as a function of finger surface temperature for fast and slow rates of cooling.

TABLE 3

MEAN PERCENTAGE OF DECREMENT FROM CONTROL PERFORMANCE

Task	Surface temperature (° Fahrenheit)			
	Cooling rate	65°	55°	48°
Block packing			4	10
Block stringing	Fast			12
	Slow		12	30
Craik screw	Fast		14	14
	Slow		14	27
Knot tying			12	28
Purdue Pegboard	Fast		8	29
	Slow	8	21	45
Screw tightening		7	20	37

sult in performance reductions no greater than 10%, even when finger surface temperature is lowered to an average of 48° Fahrenheit (8.9° Centigrade). The results of the present study also suggest minimizing requirements associated with the screw-tightening task. Screw-tightening performance was impaired on the order of 8% when finger surface temperature was lowered to only 65° Fahrenheit (18.3° Centigrade). When finger surface temperature was lowered to 48° Fahrenheit (8.9°), screw-tightening performance was reduced by 37%.

In the present study, the effects of rate and level of cooling on manual performance across tasks suggest that (*a*) manual tasks differ from each other with respect to relative dependence on aspects of manual performance; (*b*) aspects of manual performance differ, relative to each other, in their dependence on unimpaired functioning of cutaneous receptors, finger joints, muscles, and nerves, and (*c*) parameters of cold exposure interact in their effects on the hand. For example, a lower subsurface hand temperature is inferred for slow cooling than for fast cooling to a fixed level of surface temperature. Manual tasks, in fact, do differ and the factors of manipulative performance have been identified as Manual Dexterity, Finger Dexterity, Wrist-Finger Speed, Aiming, and Speed of Arm Movement (Fleishman & Ellison, 1962). Of the tasks used in the present study, the Purdue Pegboard assembly task has been identified with the Finger Dexterity factor of manipulative performance. The block-packing task is assumed to be the task in the present battery most similar to the Minnesota Rate of Manipulation-placing task which has been used to define the Manual Dexterity factor (Fleishman & Ellison, 1962). Thus, differences in response to cold exposure between the Purdue Pegboard assembly task and the block-packing task are regarded as reflecting differences between finger dexterity and manual dexterity.

The following analysis of performance on the Purdue Pegboard assembly and the block-packing tasks is illustrative of possible relationships among aspects of manipulative performance, functional integrity of the hand, and parameters of cold exposure. An important, assumed relationship between manual dexterity (manipulation of large objects) and finger dexterity (manipulation of small objects) is the increased dependence on sensory feedback from joint articulation as the manipulated object becomes smaller. Thus, when the fingers become stiff during cold exposure, and the sensory feedback is reduced, finger dexterity tasks show a greater impairment than manual dexterity tasks. In the present study, Purdue Pegboard assembly performance was impaired when finger surface temperatures were lowered to 65° Fahrenheit (18.3° Centigrade) using a slow rate of cooling or to 55° Fahrenheit (12.8° Centigrade) with a fast cooling rate. Continued slow cooling to a 48° Fahrenheit (8.9° Centigrade) finger surface temperature resulted in reductions in performance on the order of 45% By increasing object size and thereby minimizing controlled finger articulation, the size of cold induced performance decrements should be reduced, and the surface temperature level at which initial impairments occur should be lowered even with slow cooling. This relationship was found when block-packing performance during cold exposure was compared with Purdue Pegboard assembly performance.

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